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Status of the Porbeagle Shark (*Lamna nasus*) Population in the Northwest Atlantic in the Context of Species at Risk

État du requin-taupe commun (*Lamna nasus*) de l' Atlantique Nord-Ouest dans le contexte de l'espèce en péril

S. Campana, W. Joyce and / et L. Marks

Marine Fish Division
Bedford Institute of Oceanography
Dartmouth, Nova Scotia, B2Y 4A2

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Abstract

Porbeagle sharks produce few offspring and mature at a late age compared to the age of first capture. This combination of life history characteristics makes porbeagle highly susceptible to over-exploitation. The ESU for porbeagle in the NW Atlantic is represented by a single, largely Canadian population inhabiting the area from Georges Bank/Gulf of Maine to Newfoundland and the Gulf of St. Lawrence.

The virgin porbeagle population in the NW Atlantic was fished intensively at catch levels of about 4500t per year in the early 1960s before the fishery collapsed 6 years later. The population slowly recovered during the 1970s and 1980s when annual landings averaged 350t. Catches of 1000-2000t throughout the 1990s appear to have once again reduced population abundance, resulting in very low catch rates and disturbingly low numbers of mature females. Based on an extensive reconstruction of porbeagle shark abundance, all indicators of population size have declined substantially since 1961. Current population size is estimated to be 10-20% of that of the virgin 1961 population. All lines of evidence indicate that fishing mortality is largely or solely responsible for the decline in population abundance since 1961.

The most recent stock assessment indicates that catches averaging 1000t per year in the 1990s have resulted in an F of about 0.20. Life table analysis indicates that a fishing mortality above 0.08 will cause the population to decline. The current catch quota of 200-250t corresponds to a fishing mortality at or below MSY (F of 0.04-0.05), and will allow population recovery. Thus the population decline has ceased, is reversible, and will increase in numbers at a rate of about 2.5% per year. The maximum rate of increase in an unfished population is about 5% per year.

The current area of occupancy varies seasonally due to large-scale migrations. Summing across the yearly distributional range (Gulf of Maine, Scotian Shelf, southern NF, Gulf of St. Lawrence) gives a total area of about 425,000 km^2. There does not appear to have been any change in area of occupancy or degree of fragmentation since 1961.

The current estimate of mature females in the population is 6075, which is about 10% that of the virgin population 3 generations earlier.

Résumé

Le requin-taupe commun produit peu de petits et n'atteint la maturité qu'à un âge avancé par rapport à l'âge de sa première capture. Ces caractéristiques de son cycle biologique le rendent très vulnérable à la surexploitation. L'unité évolutionnaire significative du requin-taupe commun dans l'Atlantique N.-O. est représentée par une unique population qui habite en grande partie dans les eaux canadiennes allant du banc Georges et du golfe du Maine à Terre-Neuve et au golfe du Saint-Laurent.

La population vierge de requins-taupes communs de l'Atlantique N.-O. a fait l'objet d'une pêche intensive, au rythme d'environ 4 500 t par an, au début des années 1960, avant que la pêche ne s'effondre six ans plus tard. La population s'est rétablie lentement depuis les années 1970 et 1980, période où les débarquements annuels étaient en moyenne de 350 t. Des captures de 1 000 à 2 000 t tout au long des années 1990 semblent avoir à nouveau réduit l'abondance de la population, ce qui a abouti à de très bas taux de prises et à un faible nombre de femelles à maturité. Tous les indicateurs de l'effectif de la population de requins-taupes communs, fondés sur une vaste reconstitution de l'abondance de l'espèce, ont sensiblement diminué depuis 1961. On estime que l'effectif actuel représente 10 à 20 % de celui de la population vierge de 1961. Tout indique que la mortalité par pêche est grandement ou totalement responsable du déclin de l'abondance de la population depuis 1961.

Il ressort de la plus récente évaluation du stock que les captures annuelles moyennes de 1 000 t des années 1990 se sont traduites par une valeur F d'environ 0,20. L'analyse des tables de mortalité révèle qu'une mortalité par pêche supérieure à 0,08 occasionnera un déclin de la population. Le quota de prises actuelles de 200-250 t équivaut à pêcher au RMS (F de 0,04-0,05) et permettra à la population de se rétablir. Le déclin de la population a donc cessé et il est réversible; l'effectif augmentera à un taux annuel d'environ 2,5 %. Le taux maximal d'augmentation d'une population non exploitée est d'environ 5 %.

L'actuelle zone d'occupation de l'espèce varie selon la saison en raison de migrations à grande échelle. Calculée sur l'ensemble de l'aire de distribution annuelle (golfe du Maine, plateau néo-écossais, sud de Terre-neuve et golfe du Saint-Laurent), elle est au total d'environ 425 000 km^2. Il ne semble pas y avoir de changement dans la zone d'occupation ou dans le degré de fragmentation depuis 1961.

L'estimation actuelle du nombre de femelles adultes parmi la population est de 6 075, ce qui représente environ 10 % du nombre de femelles adultes présentes parmi la population vierge il y a de cela trois générations.

Background

The porbeagle shark (*Lamna nasus*) is a large cold-temperate pelagic shark species of the family Lamnidae that occurs in the North Atlantic, South Atlantic and South Pacific oceans. The species range extends from Newfoundland to New Jersey and possibly to South Carolina in the west Atlantic, and from Iceland and the western Barents Sea to Morocco and the Mediterranean in the east Atlantic. It is the only large shark species for which a commercial fishery exists in Canadian coastal waters.

Fisheries management plans for pelagic sharks in Atlantic Canada established non-restrictive catch guidelines of 1500t for porbeagle prior to 1997 (O'Boyle et al.1996). Because of the limited scientific information that was available at the time, abundance, mortality and yield calculations could not be made. Therefore, a provisional TAC of 1000t was set in place for the period 1997-1999, based largely on historic catches and the observation that recent catch rates had declined (O'Boyle et al. 1998).

In 1998, an intensive research program on all aspects of porbeagle biology and population dynamics was initiated at the Bedford Institute of Oceanography. The research was carried out with the support and funding of the porbeagle shark fishing industry, who provided ship-board access to scientific staff, as well as length measurements of more than 75% of all sharks landed. In addition, a scientific collaboration with the Apex Predators Program of the National Marine Fisheries Service (NMFS) in the U.S. provided a two-way access to both unpublished data and expertise. The combination of the BIO program, the industry support, and the NMFS collaboration greatly increased our understanding of porbeagle biology and population dynamics (Campana et al. 2002a,b; Jensen et al. 2002; Joyce et al. 2002; Natanson et al. 2002), and led to two consecutive analytical stock assessments of porbeagle (Campana et al. 1999, 2001). Based on those assessments, the Shark Management Plan for 2002-2006 reduced the TAC to 250t, a value which was calculated to be about equal to MSY and would allow stock recovery.

Life History

Age, Growth and Longevity

Natanson et al. (2002) estimated growth parameters for porbeagle shark in the northwest Atlantic Ocean on the basis of 578 vertebral annuli (Fig. 1). Annuli were validated up to an age of 11 years by using vertebrae from recaptured oxytetracycline-injected and known age sharks. Males and females grew at similar rates until the size of male sexual maturity, after which the relative growth of the males declined. The growth rate of the females declined in a similar manner at the onset of maturity. Growth curves were consistent with those derived from tag/recapture analyses (GROTAG) of 76 recaptured fish, and with length-frequency methods using measurements from 13,589 individuals. Maximum age, based on vertebral band pair counts, was 25 and 24 years for males and females, respectively. Age validation using bomb radiocarbon assays

confirmed ages of up to 26 years (Campana et al. 2002b). Longevity calculations, however, indicated a maximum age of 29 to 45 years in an unfished population.

The duration of a generation (defined as mean age of female spawners) can be approximated using estimates of female Age_{50} at sexual maturity and M. With Age_{50} ~ 13 yr (Jensen et al. 2002) and the M of mature females equal to 0.20 (Campana et al. 2001), generation length ~ Age_{50} + 1/M = 18 yr.

Reproduction

Porbeagles are ovoviviparous and oophagous, with an average litter size of around 4 pups (Francis and Stevens 1999; Jensen et al. 2002). Mean embryo size at birth is 65-75 cm (Aasen 1963; Francis and Stevens 1999). Based on examination of 393 males and 382 females, we have found that males mature between 162 - 185 cm in fork length (L_{50} ~ 174 cm; Age_{50} ~ Age 8) while females mature between 210 - 230 cm (L_{50} ~ 218 cm; Age_{50} ~ Age 13) (Jensen et al. 2002).

Until recently, the mating grounds of porbeagle were unknown, although there have been suggestions that mating occurred on the Grand Banks (O'Boyle et al. 1998) or more broadly off southern NF (Campana et al. 1999, 2001). Our most recent research indicates that mating occurs in the late summer or early fall on the Grand Banks, off southern NF and at the entrance to the Gulf of St. Lawrence (Fig. 2). Most large females collected in these areas in the fall were pregnant. Late stage embryos have only been observed on the Scotian Shelf and in the Gulf of Maine, but it is not clear if that distribution is an artifact of nonexistent sampling off southern NF in the winter or a more southerly birthing location. Birth apparently occurs in late winter or spring after an 8-9 month gestation period (Aasen 1963; Francis and Stevens 1999; Jensen et al. 2001). There is no evidence of an extended latency period after birth, since virtually all sexually mature females are pregnant in the fall (Fig. 2). Therefore, the reproductive cycle is 1 yr.

Feeding and Diet

Stomachs of 1022 porbeagle sharks ranging in size from 85-264 cm were examined from the Canadian porbeagle shark fishery and a scientific cruise in the northwest Atlantic between February 1999 and January 2001 (Joyce et al. 2002). Teleosts occurred in the majority of stomachs and constituted 91% of the diet by weight. Cephalopods occurred in 12% of stomachs and were the second most important food category consumed. Pelagic fish and cephalopods comprised the largest portion of the diet in the spring while groundfish dominated the diet in the fall. Diet did not differ significantly between the sexes. Stomach fullness differed slightly but significantly across months and declined slightly with fork length. The porbeagle is primarily an opportunistic piscivore with a diet characterized by a wide range of species. Diet composition changed seasonally following a migration from deep to shallow water.

ToR 1: Population Structure

Several lines of evidence indicate that there is only one porbeagle population in the northwest Atlantic, and that there is no appreciable mixing of porbeagle from the northeast Atlantic with those in the northwest Atlantic. Month to month shifts in the location of the fishery suggest that porbeagle carry out extensive annual migrations up and down the east coast of Canada, with no indication of the presence of separate populations (Fig. 3). Porbeagle first appear in the Gulf of Maine, Georges Bank and southern Scotian Shelf in Jan-Feb, move northeast along the Scotian Shelf through the spring, and then appear off the south coast of NF and in the Gulf of St. Lawrence in the summer and fall. Catches in the late fall suggest a return movement to the southwest. This pattern is reproducible from year to year.

The results of tagging studies carried out by Norway, Canada and the US also document extensive annual migrations (Fig. 4) (Campana et al. 1999). All three studies provided similar results, despite the fact that the Norwegian study was carried out in the 1960s (542 tagged; 53 recaptures), the US tagging was done almost every year between 1980-99 (1034 tagged; 119 recaptures), and the Canadian tagging was carried out between 1994-96 (256 tagged; 25 recaptures). Fig. 4 pools all tagging studies into one presentation, broken down by the quarter of the year in which the tags were applied, and showing only those sharks which were at liberty more than a year after tagging. Tags applied in the first half of the year tended to be recaptured at more easterly and northerly locations, while the reverse was seen for tags applied in the summer and fall. Many porbeagle were recaptured 500-1000 km from the point of tagging (Fig. 5), and movement between the Grand Banks, the Scotian Shelf and the Gulf of Maine was not uncommon. Seasonal shifts in fishing effort cannot fully account for the large-scale migration pattern, since sharks tagged at the same time of year as their recapture also showed substantial movements, although perhaps not of the same scale (Fig. 4 – bottom panel). None of the tagged porbeagle were recaptured on the east side of the Atlantic, and none of the porbeagle tagged in the eastern Atlantic were recaptured off the North American coast.

Summary

The ESU for porbeagle is represented by a single population inhabiting the area from Georges Bank/Gulf of Maine to Newfoundland and the Gulf of St. Lawrence. The ESU is not completely restricted to Canadian waters, although it is essentially a Canadian population.

ToR 2a: Declining Total Population: Overall Trends in Population Size

Landings

The fishery for porbeagle sharks in the Northwest Atlantic (NAFO areas 3 - 6) started in 1961 when Norwegian vessels began exploratory fishing on what was then a virgin population (Fig. 6). These vessels had previously fished for porbeagle in the Northeast Atlantic. They were joined by vessels from the Faroe Islands during

the next few years. Reported landings in the northwest Atlantic rose from about 1,900t in 1961 to over 9,000t in 1964 and then fell to less than 1,000t in 1970 as a result of a collapse of the fishery. Although the fishery was unrestricted, reported landings were less than 500t until 1989. Reported landings rose to about 2,000t in 1992, due to increased effort by Faroese vessels and also due to the entry of Canadian interests into this fishery. Faroese participation was phased out of the directed fishery by 1994, at which time total landings by three Canadian offshore pelagic longline vessels and a number of inshore vessels was about 1600t. Since that time, the fishery has been almost exclusively Canadian, with landings declining gradually to about 1000t in 1998. Landings from 1998 onwards have been restricted by quota control, and were less than 250t in 2002.

Due to the directed nature of the fishery, the accuracy of the landings data appears to be excellent. Nevertheless, makos are morphologically similar to porbeagles, and it is possible that small numbers of makos were misidentified as porbeagles at the time of landing, particularly in the early 1990s when the Canadian fishery was new. Given that reported mako landings have always been less than 10% of reported porbeagle landings (Campana et al. 2001), any misidentifications in the landings data would have no appreciable impact on the landings trends.

Trends in Length Composition

A biological indicator of increased exploitation rate is a long-term decline in fork length in the catch. A plot of median fork length against year of collection showed a long-term decline in length composition on the NF-Gulf mating ground in early fall (Fig. 7). The median lengths for the years prior to 1980 are most representative of the length composition of a lightly fished population. In contrast, 1999 and 2000 were characterized by very low median sizes, indicating the loss of many sharks of mature size.

Commercial Catch Rates

Calculations of catch rate were based on directed longline catches, which account for virtually all historical catches. Most of the directed effort has traditionally come from the offshore fleet, both foreign and Canadian. However, effort from the inshore fleet became substantial in 1996 when exploratory licences first became available, and the same year that one of the 3 offshore vessels was removed from the fishery. Effort trends and the balance between inshore and offshore have been relatively stable since then.

Catch rate measures were disaggregated into those for immature and those for mature sharks; both were calculated in terms of ln-transformed numbers per hook. A fork length equal to 200 cm is approximately midway between the lengths corresponding to 50% maturity in males and females, and is therefore a proxy for sexually mature porbeagles. To calculate catch rate at length, length composition was determined for each of 3 subareas (south Shelf, east Shelf and NF-Gulf) in each of 3 seasons (Jan-Mar, Apr-June, July-Dec) for each year based on available measurements. Set by set catch rates in terms of weight were converted to numbers based on the mean weight of the length composition

of the subarea-season-year cell, then apportioned according to the length frequency. Numbers above 200 cm FL were pooled within a set to form the index for mature sharks, while the remainder were pooled to form the index for immature sharks.

The overall trend in catch rate was analyzed using a linear model with subarea, month, CFV and year as factors. All factors were significant in the model predicting the catch rate of mature porbeagles. Several interaction terms were also significant, but their inclusion did not change the overall trend in catch rate, which is shown in Fig. 8. The standardized catch rate of mature porbeagles increased significantly between 1989 and 1992, but declined sharply afterwards as effort increased and the abundance of the large sharks declined. The 2000 point is the second lowest in the time series, and is 10% of the 1992 value. The standardized catch rate model for immature porbeagles was also highly significant, and also showed a significant decline since the early 1990s (Fig. 8). The 2000 point is about 30% of the 1991 point. However, the catch rate has remained roughly stable since 1996 (ignoring the 1997 value, which is anomalously low in the mature CPUE series), consistent with the fleet-specific catch rates. Overall, these catch rates suggest a monotonic and disturbing decline in the abundance of mature sharks, with a low but stable rate for immature sharks.

Age- and Sex-Structured Population Model

A forward-projecting, age- and sex-structured population dynamics model was developed for NW Atlantic porbeagle in order to estimate current population status relative to that of earlier years. The model was fit to available catch at length and CPUE data between 1961-2000, using the growth model, natural mortality rates, maturity ogives, fecundity and area-season stratification described in Campana et al. (2001). The steepness of the Beverton-Holt spawner-recruit model was defined *a priori* as 0.37 on the basis of the well-defined reproductive parameters of porbeagle. Model output included time trends in biomass, female spawner numbers and area-specific selectivity curves. AD Model Builder was used to prepare the model and fit the likelihood functions.

The base model assumed a combined growth curve, a higher M in the first year of life, an increased M at the onset of sexual maturity, and a fixed selectivity. Both total biomass and spawning stock numbers were modelled as declining sharply after the onset of the 1961 fishery, recovering slightly through the 1970s and 1980s, then declining once more to a record low level (Fig. 9). Current biomass was estimated as being 11% of virgin biomass and fully recruited F in 2000 was estimated as 0.26 (Table 1). The time series of fishing mortality indicates that F has been very high since the mid 1990s.

Four alternative model runs are presented in Table 1; all are similar to or more pessimistic than the base run. The most viable of the alternative runs (run 5) was one in which both selectivity and recruitment deviates were estimated, and there was no increase in M at maturation. The time trend in biomass was very similar to

that of the base run, with similar terminal F (=0.26) but a slightly higher terminal biomass (17% of virgin biomass).

The reference points from the model were similar in all runs. MSY was 1000-1200t at an F_{MSY} of 0.04-0.05 (Table 1).

Peterson Calculations of Abundance and Exploitation Rate

The abundance of both the virgin porbeagle population of the 1960s and that of the fished population in the 1990s was estimated through Peterson analysis of tag recaptures. While the Peterson calculations are straight forward, certain assumptions must be made concerning rates of tag loss, tag-induced mortality and the probability of non-reporting. The results were not particularly sensitive to these assumptions; however the fact that many large sharks were tagged in the 1960s, but not in the 1990s, makes the population comparison between recent and historic times somewhat tenuous. With this caveat in mind, the independent tagging studies of the US and Canada provided similar estimates of population biomass between 1994 and 1997. These population estimates were about 15-20% of the size of the virgin population tagged by the Norwegians (Fig. 10).

Petersen calculations of recent exploitation rate are relatively insensitive to the above assumptions, and thus are reasonably robust. Exploitation rate between 1994-2000 was estimated to lie between 5-20%, with a mean of about 11%.

Summary

All indicators of population size have declined substantially since 1961. Current population size is estimated to be 10-20% of that of the virgin population in 1961.

ToR 2b: Causes of the decline in abundance

The time series of porbeagle shark abundance has been reconstructed based on several independent and extensive data sources. All lines of evidence indicate that fishing mortality is largely or solely responsible for the decline in population abundance since 1961.

ToR 2c: Are the declines reversible?

Life Table Analysis

Life table analysis uses age-structured estimates of survival rate, sexual maturation and fecundity to project population growth under various scenarios. It is well suited for use in sharks given their well-defined reproductive cycle and high rates of survival (Cortés 1998).

Table 2 presents the life table analysis for porbeagle. The values of M, maturity ogive and fecundity were as presented earlier. Fishing mortality was added to M to investigate various fishing strategies, subject to area-specific selectivities. A fishery in which all ages were fully selected was also investigated. The results indicated

that the intrinsic rate of population growth (r) in an unfished population varied between 0.05-0.07 depending on the natural mortality assumptions which were made. Such values are very low compared to most fishes (Myers et al. 1999), and indicate that the porbeagle population is intrinsically unproductive and slow to recover from stock depletion. Fishing mortalities on the order of 0.18 resulted in population decline under all scenarios. A fishing scenario with F=0.08 resulted in population decline when the selectivity of the mature fish was high (eg- in NF-Gulf) and produced only marginal growth when mature selectivity was low (eg- on the Shelf). F=0.08 corresponded to zero population growth using the combined PR vector, and thus serves as the reference point for $F_{replacement}$. A value equal to one half of $F_{replacement}$ (= 0.04) allows both population growth and a catch. This value is very similar to that of F_{msy} estimated from the population model.

Summary

The most recent stock assessment indicates that recent catches averaging 1000t per year have resulted in an F of about 0.20 (Fig. 11). Life table analysis indicates that a fishing mortality above 0.08 will cause the population to decline, and that a fishing mortality of 0.04-0.05 will allow the population to recover. The current catch quota of 200-250t corresponds to fishing at or below MSY, and will allow population recovery. To some extent, the selection of any particular F within the range that will allow population recovery is arbitrary. Nevertheless, catches at F=0.04 allow both population recovery and continued catches for population monitoring; since both recovery and monitoring are required, this level of fishing appears to strike an appropriate balance.

The decline in abundance of the porbeagle population has ceased, is reversible, and will increase in numbers at a rate of about 2.5% per year. The maximum rate of increase in an unfished population is about 5% per year.

ToR 3: Distribution

Temperature and Depth Associations

Porbeagle appear to occupy well defined temperatures throughout the year. To examine the influence of temperature on porbeagle distribution, a detailed analysis of the relationship between catch rate, temperature, depth and location was carried out based on 420 temperature profiles taken during commercial fishing operations (Campana et al. in press). More than half of the porbeagle were caught at temperatures of 5-10^0 C (at the depth of the hook); the mean temperature-at-gear of 7.4^0 C differed very little among seasons (Fig. 12c). Most of the spring fishing took place near fronts (Fig. 13), although the affinity with fronts was not evident in the fall. Temperature-at-depth was a significant modifier of catch rate when included in a generalized linear model controlling for the effects of location, fishing vessel, month and year. However, sea surface temperature was a poor predictor of catch rate. The similarity between environmental and catch-weighted cumulative distribution functions confirmed suggestions that fishers sought out the most appropriate temperature range in which to set their gear. Since porbeagle are among the most cold-tolerant of

pelagic shark species, we suggest that they have evolved to take advantage of their thermoregulating capability by allowing them to seek out and feed on abundant coldwater prey in the absence of non-thermoregulating competitors.

Water depth was not correlated with porbeagle catch in the spring; depth varied between 200-2800 m (Fig. 12a). In contrast, fall catches were made in much shallower waters, most often at depths of less than 150 m (Fig. 12b).

Location and Size Composition of the Catch, with Inferences on Migration

The overall pattern of catch location and size composition since 1999 is shown in Fig. 14. Both the inshore and offshore fleets fished the Scotian Shelf in the spring of 1999 and 2000, although the offshore fleet tended to fish near the edge of the continental slope while the inshore fleet fished well onto the shelf. The size composition of the catch of both fleets was very similar. In May, the offshore fleet moved into the waters off of southern NF. Fishing by both fleets was minimal during the summer months. In the fall, the small amount of catch taken by the inshore fleet was mainly from the Scotian Shelf, while the much larger offshore catches were made in the Gulf of St. Lawrence, off southern NF, and on the Grand Banks (Fig. 14). Large sharks were more common in the fall catch off of southern NF.

Closer examination of the month to month shifts in length frequency in Fig. 15 suggests a seasonal migration of the larger sharks (>180 cm FL) along the Scotian Shelf towards NF in the spring. This pattern is evident in both the inshore and offshore length frequencies, whereby the relative abundance of the mode for larger sharks on the Shelf decreases substantially between March and May, appearing off NF in May. The change in the mode was most apparent in the offshore fishery along the edge of the Shelf, suggesting that the migration route might occur along the Shelf edge. A more detailed analysis of sex ratios in the monthly catch broken down by area strongly suggests a springward migration of mature sharks, particularly males, along the Shelf towards the NF mating grounds (Campana et al. 2001). This would suggest that the Scotian Shelf serves as the residence for mainly immature sharks, characterized by more limited migratory movements. Analysis of tagging data confirms that small sharks are less likely to move long distances than are larger sharks (Fig. 5).

Summary

The current area of occupancy varies seasonally due to large-scale migrations. Summing across the yearly distributional range (Gulf of Maine, Scotian Shelf, southern NF, Gulf of St. Lawrence) gives a total area of about 425,000 km^2.

There does not appear to have been any change in area of occupancy since 1961.

There is no evidence suggesting a fragmentation of the population.

ToR 4: Small Population Size

The current estimate of mature females in the population is 6075 (Table 1).

The current population represents about 10% that of the virgin population in 1961 (~ 3 generations earlier).

Conclusions

Porbeagle sharks produce few offspring and mature at a late age compared to the age of first capture. This combination of life history characteristics makes porbeagle highly susceptible to over-exploitation. Average catches of about 4500t per year in the early 1960s resulted in a fishery which collapsed after only 6 years, and which did not recover for another 25 years. However, the fishery appeared sustainable during the 1970s and 1980s when landings averaged 350t annually, and the population slowly recovered. Catches of 1000-2000t throughout much of the 1990s appear to have once again reduced population abundance, resulting in lower catch rates and disturbingly low numbers of mature females.

The current porbeagle population is seriously depleted, but is now reasonably well understood. Due to the low productivity of the species, recovery will not be rapid, even in the complete absence of fishing. However, the current and future catch quotas are much lower than the sustainable level, and thus will allow population growth.

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Table 1. Age- and sex-structured population model for porbeagle, fit to catch at length and CPUE data by season/area.

Run	Details	Female spawners					Total biomass (000t)					Exploitation rates in 2000			
		1961	1991	2001	1991/1961	2001/1961	1961	1991	2001	1991/1961	2001/1961	Age 2	Age 5	Age 8	Ln likelihoo
base	Base case: M increases at maturity; fixed selectivity; combined growth curve	63694	16618	6075	0.26	0.10	38967	13260	4409	0.34	0.11	0.16	0.25	0.26	-543
run2	As above but with no recruitment deviates	64710	18385	7500	0.28	0.12	39589	14357	4991	0.36	0.13	0.14	0.22	0.23	-405
run3	Estimating selectivity and recruitment deviates	69186	15048	2612	0.22	0.04	42327	12461	1572	0.29	0.04	0.41	0.64	0.80	-1005
run4	Estimating selectivity without recruitment deviates	69664	15273	2934	0.22	0.04	42619	12908	1928	0.30	0.05	0.35	0.52	0.65	-992
run5	Estimating selectivity and recruitment deviates with no increased mortality	100979	29606	13847	0.29	0.14	44317	16500	7695	0.37	0.17	0.14	0.21	0.26	-918

		B0	Fmsy	MSY/B	MSY(t)	Bmsy/B0	Bmsy	B2001	B2001/Bmsy
base	Base case	38967	0.046	0.027	1069	0.63	24402	4409	0.18
run2	As above but with no recruitment deviates	39589	0.046	0.027	1086	0.63	24791	4991	0.20
run3	Estimating selectivity and recruitment deviates	42327	0.047	0.027	1138	0.62	26362	1572	0.06
run4	Estimating selectivity without recruitment deviates	42619	0.047	0.027	1143	0.62	26519	1928	0.07
run5	Estimating selectivity and recruitment deviates with no increased mortality	44317	0.063	0.024	1079	0.48	21275	7695	0.36

Table 2. Life table analysis of porbeagle shark, including simulations under various fishing strategies. The intrinsic rate of population growth (r) must be greater than 0 if the population is to grow.

Input parameters:

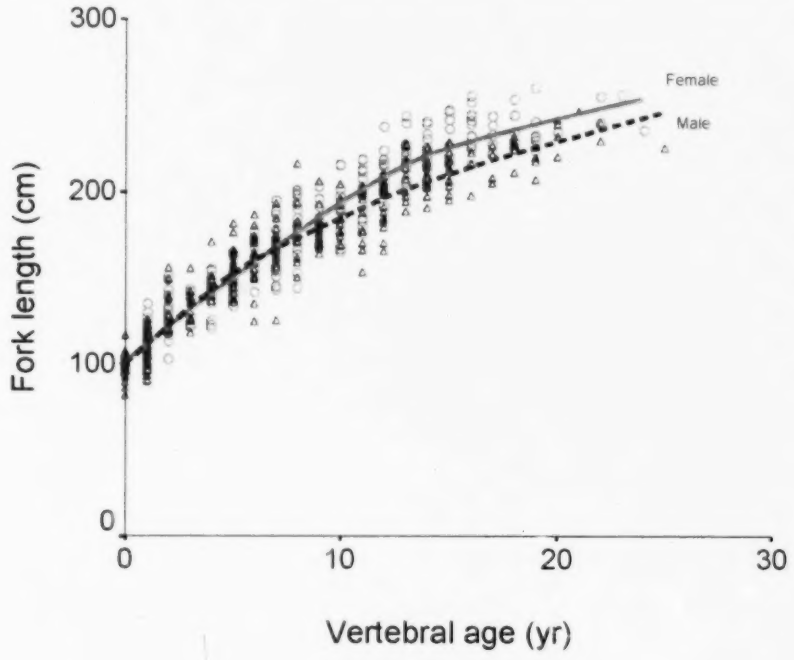
F=	0.00
Mo = (first yea	0.20
Mi = (immature)	0.10
Mm= (mature)	0.20
Tmat=	13
Tmax=	45
Fec (mx) > age	1.95

			Selectivity		
Age (x)	Fecundity	Fec/2	Area Shelf	Area NF	Combined 2:1
0	0	0	0.05	0.05	0.05
1	0	0	0.40	0.15	0.32
2	0	0	0.70	0.20	0.53
3	0	0	1.00	0.30	0.77
4	0	0	1.00	0.50	0.83
5	0	0	1.00	0.60	0.87
6	0	0	1.00	0.75	0.92
7	0	0	1.00	0.90	0.97
8	0	0	0.80	0.95	0.85
9	0	0	0.60	1.00	0.73
10	0	0	0.40	1.00	0.60
11	0.35	0.18	0.20	1.00	0.47
12	0.90	0.45	0.10	1.00	0.40
13	1.95	0.98	0.10	1.00	0.40
14	3.00	1.50	0.10	1.00	0.40
15	3.28	1.64	0.10	1.00	0.40
16	3.74	1.87	0.10	1.00	0.40
17	3.86	1.93	0.10	1.00	0.40
18	3.90	1.95	0.10	1.00	0.40
19	3.90	1.95	0.10	1.00	0.40
20	3.90	1.95	0.10	1.00	0.40

Life Table Analysis Model Output

Mo	Mi	Mm	F	electivit	r
0.2	0.1	0.1	0	0	0.071
		0.2			0.051
		$F_{replacement}$ =	0.080	1	-0.028
				Shelf	0.012
				NF	-0.005
				Both	0
		F_{key} =	0.04	1	0.013
				Shelf	0.031
				NF	0.024
				Both	0.029

Fig. 1. Growth curve for porbeagle shark, showing a reduction in growth rate for both sexes at the age of sexual maturity. Fitted lines are LOESS by sex. The age-length table is based on the von Bertalanffy growth model, substituting observed lengths for ages 0 and 1. Ages have been validated to age 26.



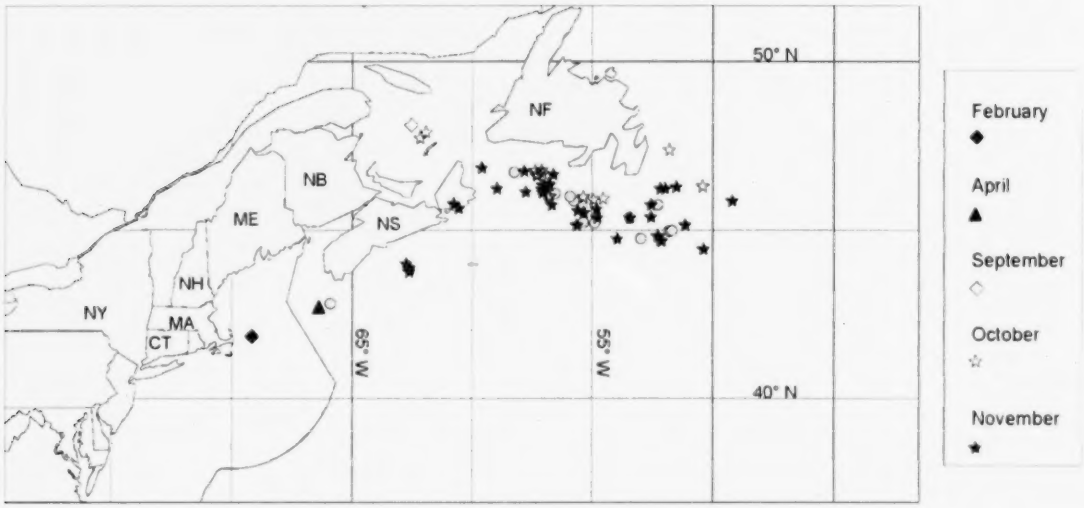
Age	FL (cm)	Wt At age (kg)
0	68	4.68
1	100	13.33
2	119	21.38
3	130	27.17
4	140	33.22
5	149	39.34
6	158	46.12
7	166	52.74
8	174	59.92
9	181	66.69
10	188	73.92
11	195	81.63
12	201	88.62
13	206	94.73
14	212	102.40
15	217	109.09
16	221	114.63
17	226	121.81
18	230	127.74
19	233	132.31
20	237	138.57

Von Bertalanffy growth model

$$L_t = L_\infty (1-e^{-K(t-t_0)})$$

	L_∞	K	t_0	N
Combined	289.4	0.066	-6.06	576
Male	257.7	0.080	-5.78	283
Female	309.8	0.061	-5.90	291

Fig. 2. (Top) Locations of pregnant female porbeagle sharks. Females give birth to an average of 4 pups in late winter or early spring. (Bottom) Monthly progression of pregnancy in females of mature size. The gestation period is 8-9 months while the reproductive cycle is 1 year.



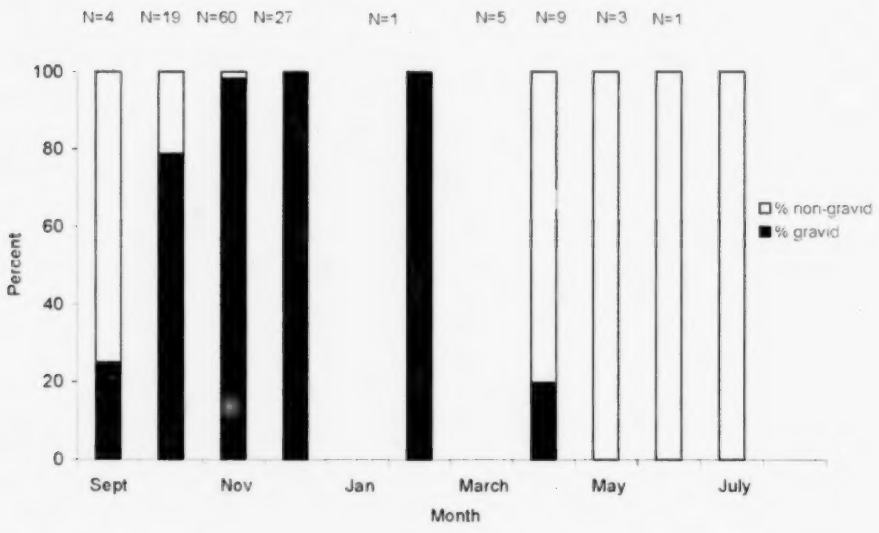
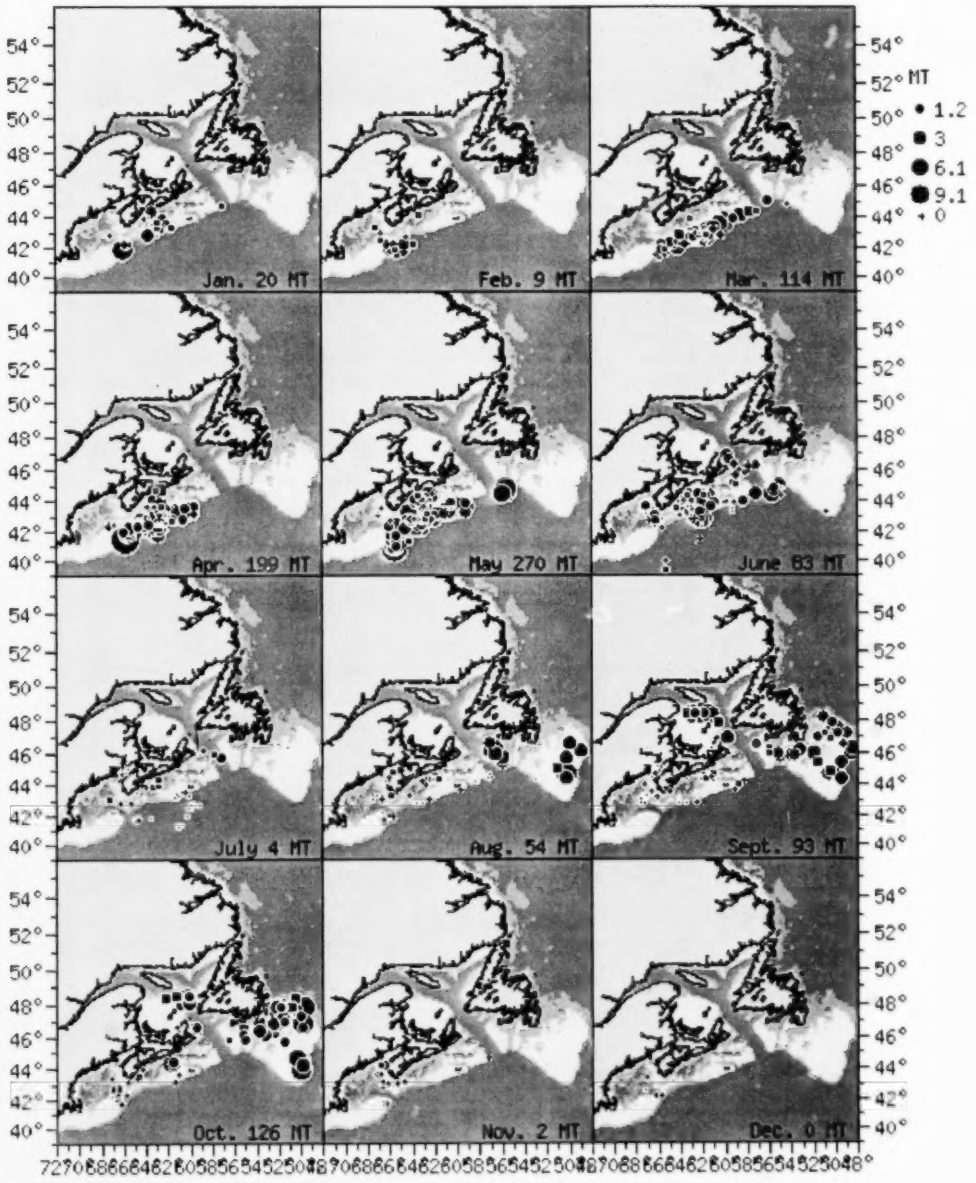


Fig. 3. Overview of porbeagle shark distribution and seasonal migration pattern based on monthly catch locations in the 1998 fishery.



704 subtrips
975 MT

Fig. 4. Annual migration of porbeagle based on Norwegian, American and Canadian tagging studies.

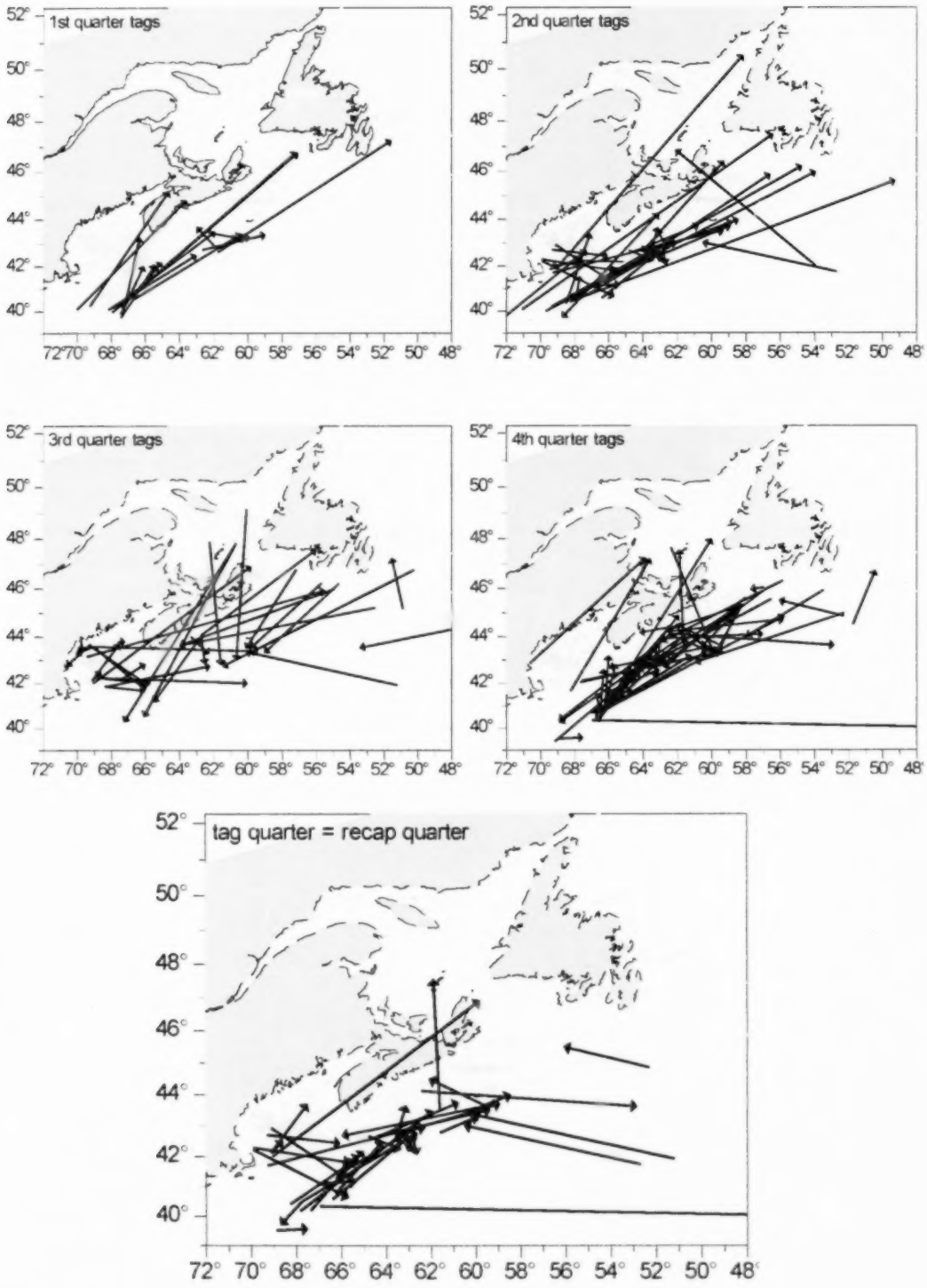

1st quarter tags
2nd quarter tags
3rd quarter tags
4th quarter tags
tag quarter = recap quarter
52° 50° 48° 46° 44° 42° 40°
72° 70° 68° 66° 64° 62° 60° 58° 56° 54° 52° 50° 48°

Fig. 5. Distance travelled versus forklength at recapture for tagged sharks at liberty > 1 yr. A LOESS curve has been fitted to the data. Larger sharks tend to travel further.

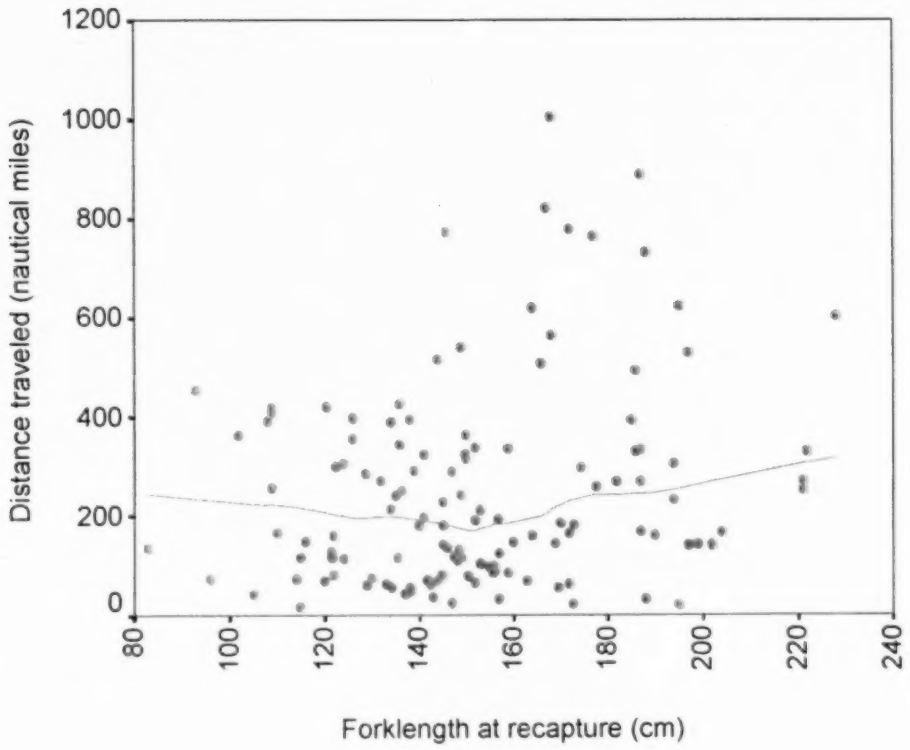


Fig. 6. Reported landings of porbeagle in the NW Atlantic by country.

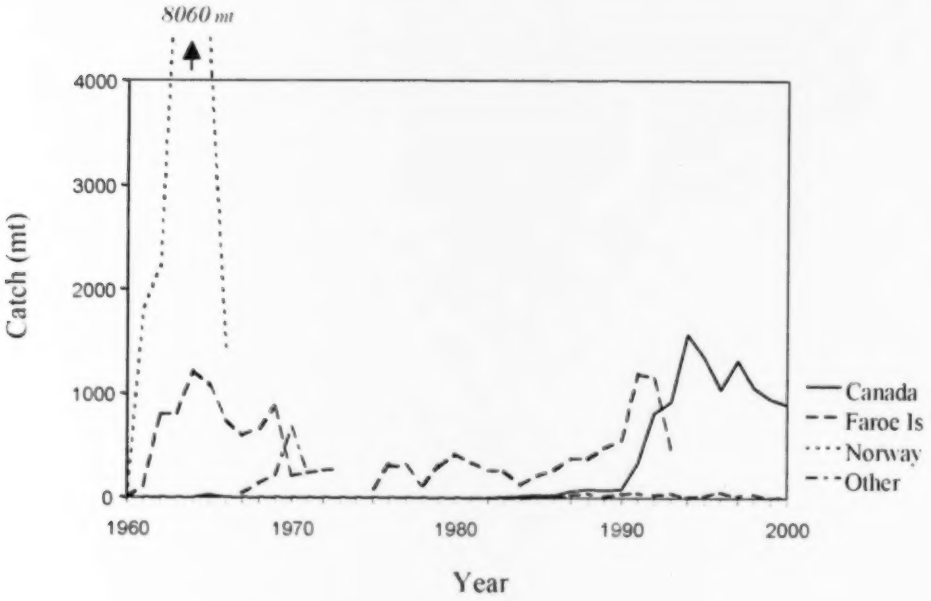


Fig. 7. Long term changes in the median fork length of porbeagle in the commercial catch by the offshore fleet on the mating grounds.

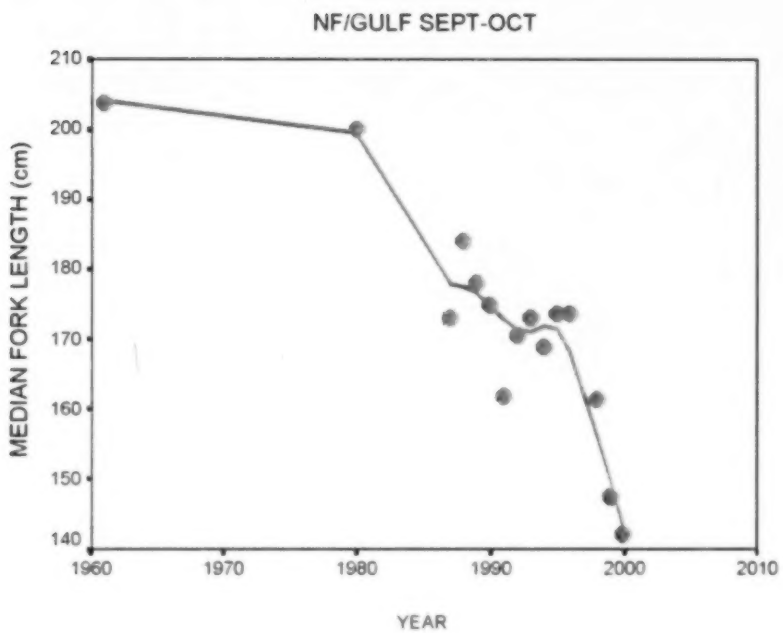
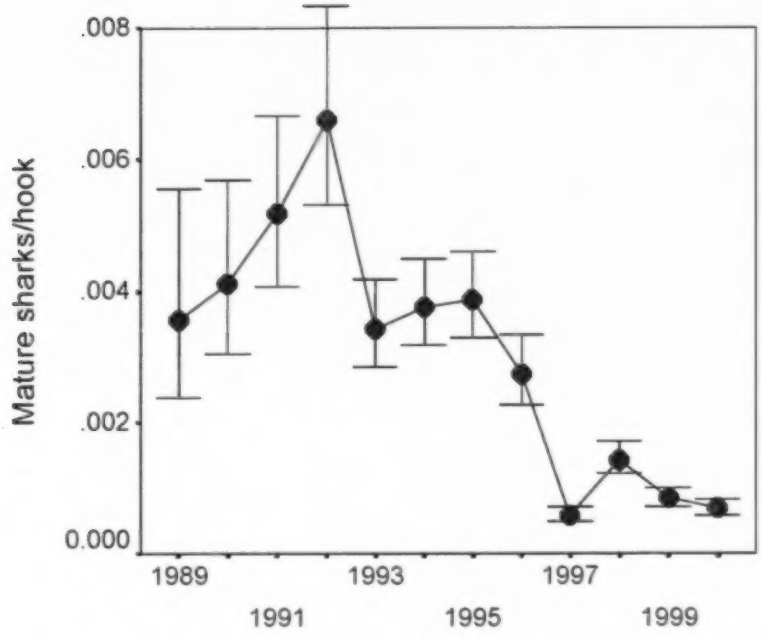


Fig. 8. Standardized catch rate (number/hook) of sexually mature (>200 cm FL) and immature porbeagle shark. Factors in the analysis included year, month, area and CFV.



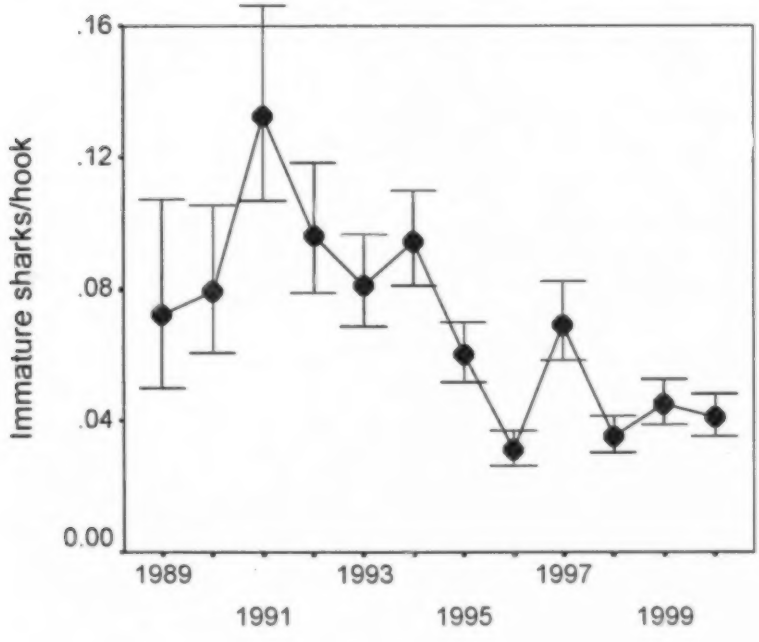


Fig. 9. Time trends in porbeagle biomass and spawner abundance from the base case model. Vertical axes are shown on a log scale.

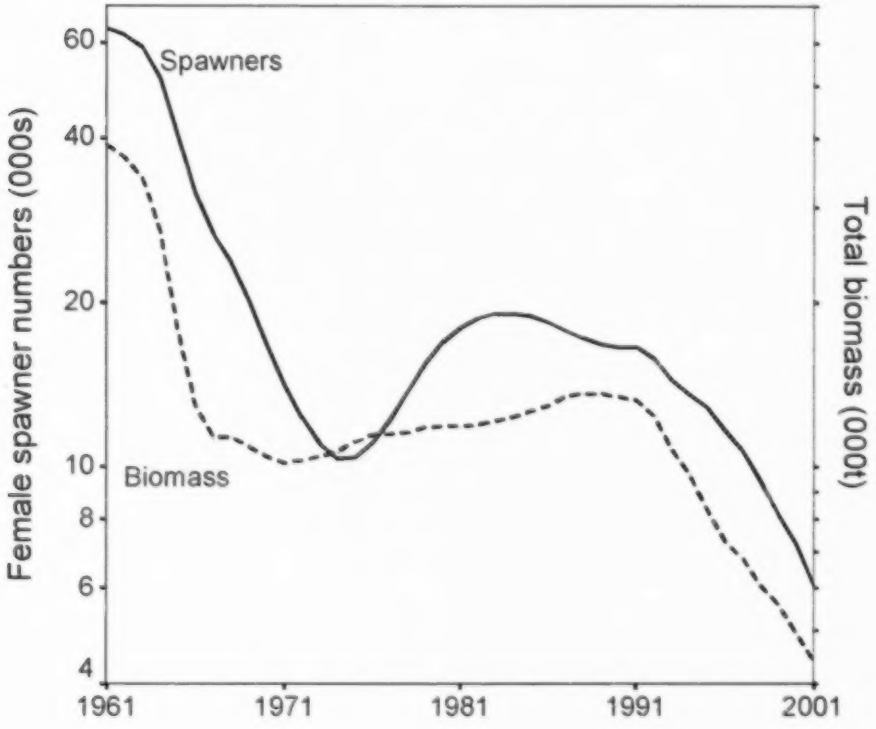


Fig. 10. Estimates of population biomass (mt) based on Peterson analysis of tag recaptures from Canadian, American and Norwegian tagging studies. Only years with more than 4 recaptures from a given tagging year are shown.

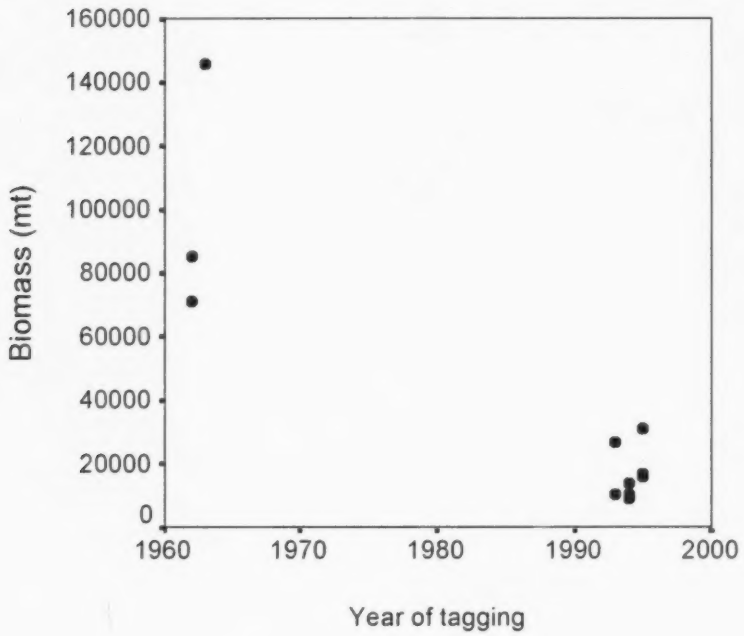


Fig. 11. Summary of recent fishing mortality (F) estimates derived from independent analyses. Estimates are drawn from analysis of the years 1994-2000 (tagging), 1998-2000 (Palohemo Z's), 1999-2000 (average weights), and 2000 (population model). The approximate range of uncertainty is indicated. All estimates of recent F are well above a level which is sustainable.

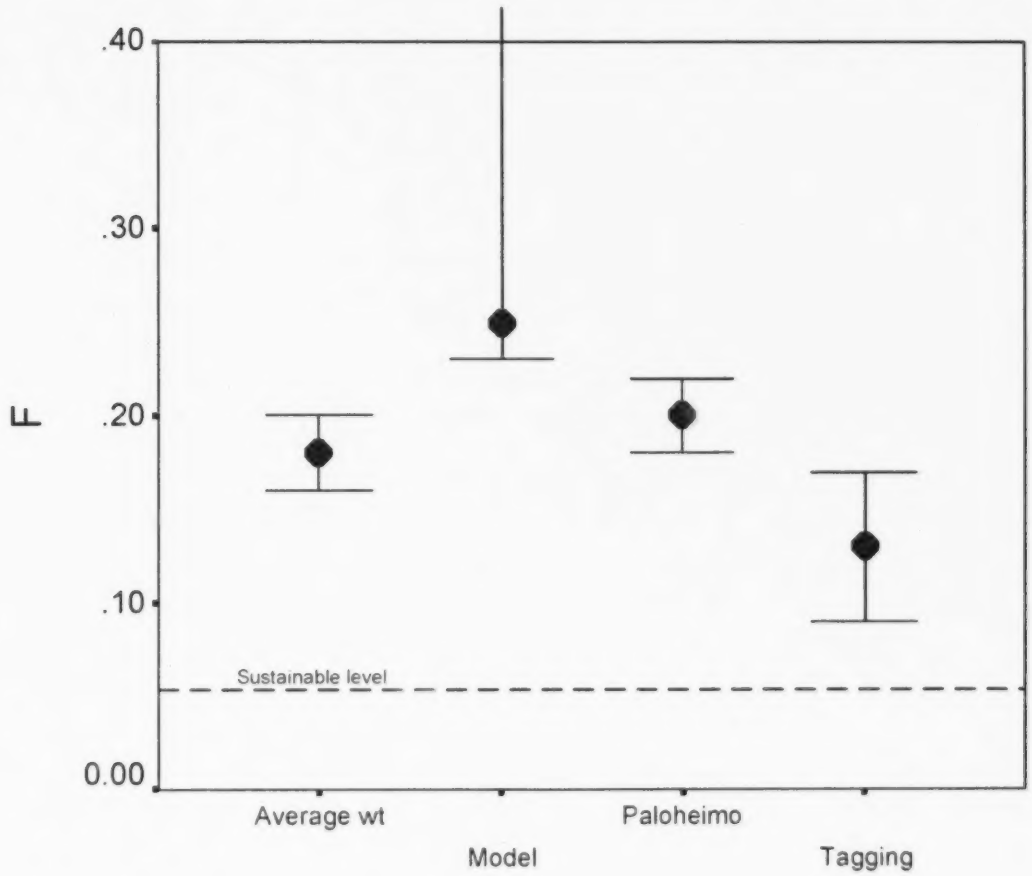
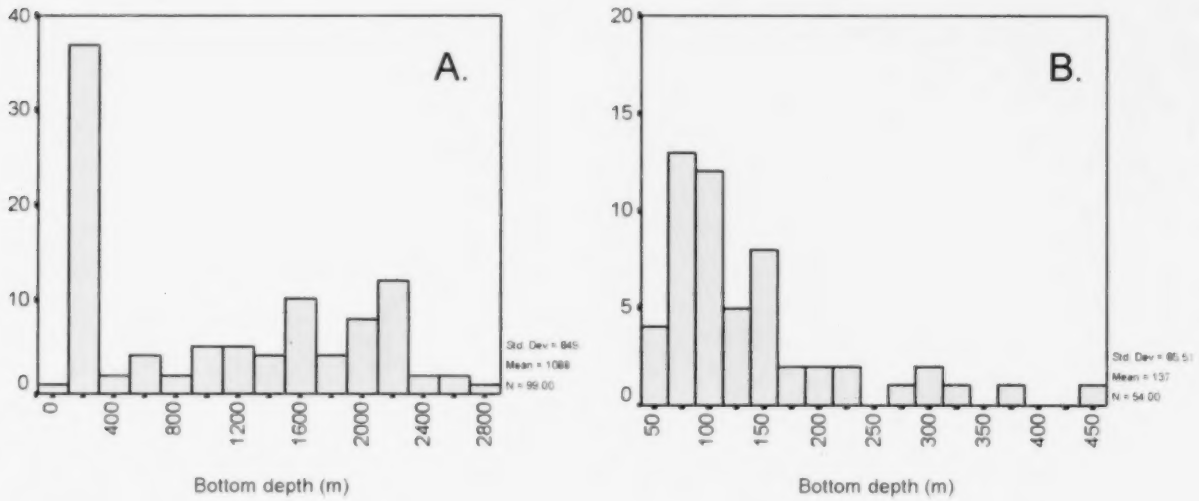


Fig. 12: Histograms of bottom depth for spring (A) and fall (B) porbeagle fisheries, and month by month error bar plot of temperatures associated with catch (C) for 1999.



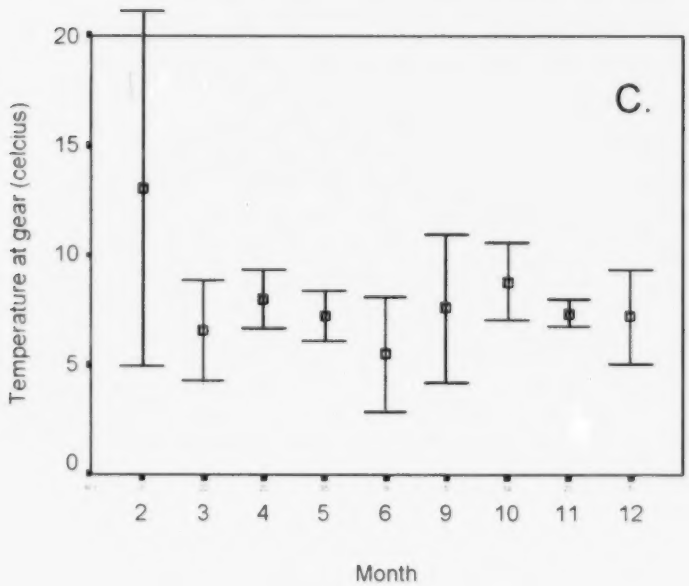


Fig. 13: Catch and associated temperature at mid-gear depth for 1999.

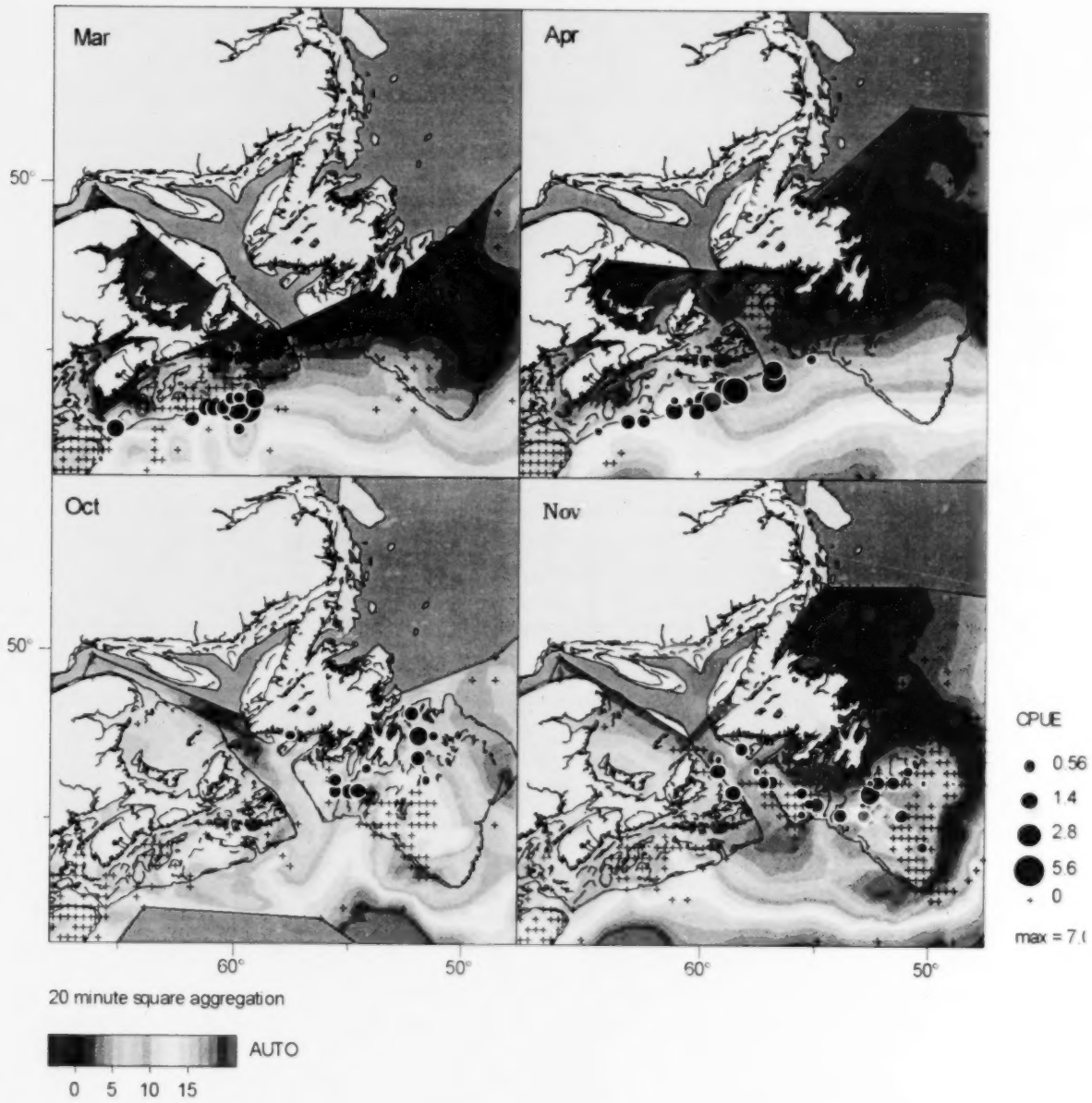


Fig. 14. Seasonal catch location and size composition of porbeagle in the 1999-2000 fisheries.

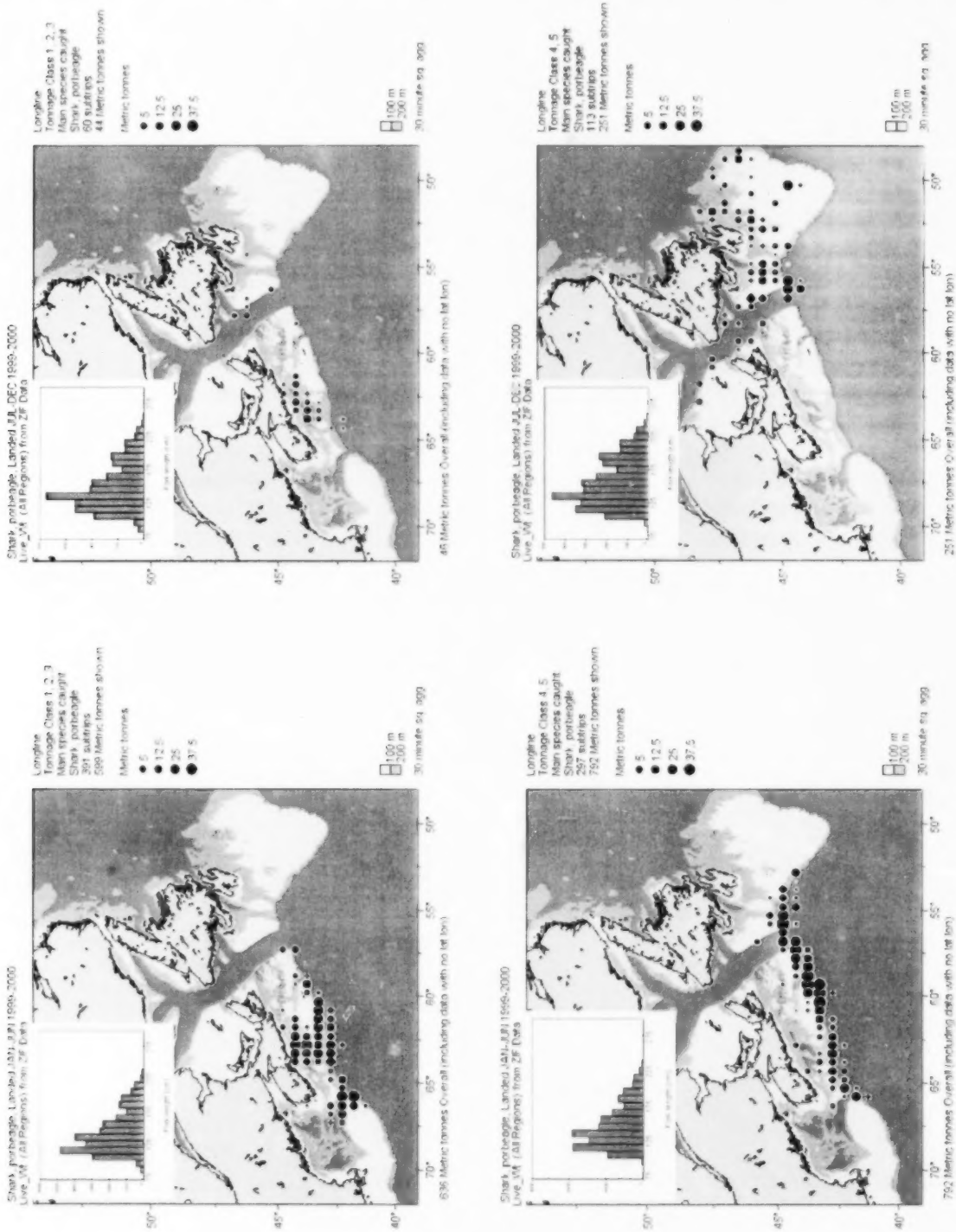


Fig. 15. Length composition of porbeagle catches in the 2000 spring and fall fishery.